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Influence of inherited geometry and fault history on the seismogenic activity and potential of strike-slip fault systems in NW Slovenia: the case study of the Ravne Fault.

VANJA KASTELIC (*, °), PIERFRANCESCO BURRATO (*) & MARKO VRABEC (°)

RIASSUNTO

L'influenza delle geometrie ereditate e della storia della faglia sulla segmentazione e il potenziale sismogenetico dei sistemi trascorrenti in Slovenia nord-occidentale: la Faglia di Ravne.

La zona di faglia Ravne è situata in un area di interazione fra due sistemi regionali di faglie con differente cinematica, entrambi collegati alla convergenza fra Adria e Eurasia: le faglie dinariche orientate NW-SE e le faglie del Sud-alpino orientate E-W.

L'analisi di dati di geologia strutturale e di due sequenze sismiche recenti che hanno colpito l'area, ci permette di proporre un modello sismotettonico per la faglia di Ravne, che è stata interessata da diverse fasi tettoniche. La geometria originale e la storia evolutiva della zona di faglia svolgono un ruolo cruciale nella distribuzione recente dell'attività sismica e del potenziale sismogenetico dell'intera struttura. Infatti, la configurazione attuale della faglia Ravne, caratterizzata da fagliazione trascorrente su piani ad alto angolo a profondità crostali, è il risultato dell'iniziale geometria di un thrust orientato NW-SE e avente immersione verso NE, e della sua interazione con i piani di thrust diretti essenzialmente E-W. Partendo dai dati raccolti e tenendo in considerazione sia il quadro geodinamico che le relazioni empiriche, proponiamo tre possibili scenari con relativi potenziali sismogenetici per la possibile futura attività della faglia di Ravne.

Key words*: fault geometry, fault growth and linkage processes, reactivation, seismicity.*

INTRODUCTION

In this work we study the influence of the inherited structural pattern and the fault history on the segmentation and seismogenic potential of the Ravne Fault, a fault zone located in the eastern Southern Alps. We also present a model of development of the Ravne fault, as a fault zone, which has undergone multiple tectonic phases. The emphasis of this work is on the fault's seismic activity and its related seismogenic potential. For this purpose we analyzed surficial geological and structural data to study the fault geometry and the microkinematic indicators present within the fault zone. We also carried out a detailed study of the spatial, temporal and kinematic characteristics of the 1998 and 2004 seismic sequences.

The Ravne Fault is a NW-SE trending, right-lateral strike-slip fault that lies in the western Julian Alps of NW Slovenia. In this area the NW-SE oriented faults, typical of the Dinaric domain, meet and interact with the E-W oriented faults of the South Alpine domain (e.g. CASTELLARIN & CANTELLI, 2000; DOGLIONI, 1987; PAMIĆ *et alii*, 2002). The activity of both structural trends is controlled by the Adria-Europe relative convergence, that in the study area results in about 2 mm/a of N-S oriented shortening (WEBER *et alii*, 2006, GRENERCZY *et alii*, 2005). This deformation is seismically released by thrust faulting earthquakes along the Eastern Southern Alps fronts, and by right-lateral strike-slip faulting along the Dinaric system (e.g. BURRATO *et alii*, 2008; DISS WORKING GROUP, 2007).

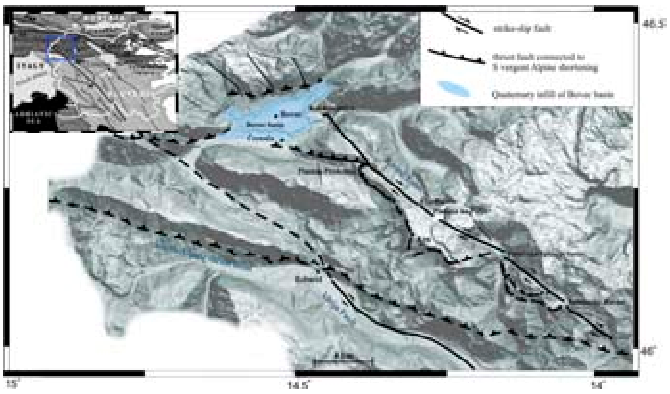

Fig. 1 – Map of the main faults in the NW Slovenia, with the emphasis on the geometry of Ravne Fault. In the upper left corner a regional tectonic framework with depicted main structures is shown; blue rectangle showing area of investigations of this study.

STRUCTURAL SETTING

The morphological expression of the Ravne Fault can be observed in the field and on satellite and digital topographic imagery over a distance of approximately 30 km in a NW–SE direction (Fig. 1) between Kal Koritnica in the NW and Cerkno at the SE end (KASTELIC *et alii*, 2008). The fault trace is discontinuous, interrupted by local transtensional basins arranged in a right stepping manner. The fault zone consists of individual NE-dipping fault planes with different dip angles. The shallower dipping planes, with values between 40°-60°, usually represent the contact between Cretaceous flysh rocks in

(*) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Sismologia e Tettonofisica, Roma, Italy

(°) Department of Geology, Faculty of Natural Sciences and Engineering, University of Ljubljana, Askerceva 12, 1000 Ljubljana, Slovenia

the foot-wall and Triassic limestones in the hanging-wall. In places, where such planes are present within the limestones, shear zones are also present. The geometry of the planes and the shear bands indicate uplift of the hanging-wall blocks. Well developed cataclastic zones up to a few centimetres wide are developed adjacent to some planes, whereas in other places, sheared surfaces of polished tectonic breccia occur in the innermost fault zone. Fault-related deformation on moderatly dipping fault planes is not confined only to the steep trace of the Ravne Fault, but is rather well recorded also on fault planes of the foot-wall block. Where preserved, microkinematic indicators on these planes prove dip slip displacements. Planes with steeper dips reaching values of more then 75 degrees in most cases lack of microkinematic indicators. Throughout the outcrops along the trace of the fault zone, only individual subvertical planes with visible striation marks and horizontal grooves showing strike-slip movement are present. In places, also (sub)vertical fractures cutting through the more shallowly dipping thrust planes can be observed at the surface, indicating the propagation towards the surface of the steep subvertical planes forming at depth (KASTELIC *et alii*, 2008).

Recent seismicity recorded in the Ravne Fault zone shows that ongoing seismic activity is confined to shallow crustal levels and does not exceed depths beyond 10 km. The 1998

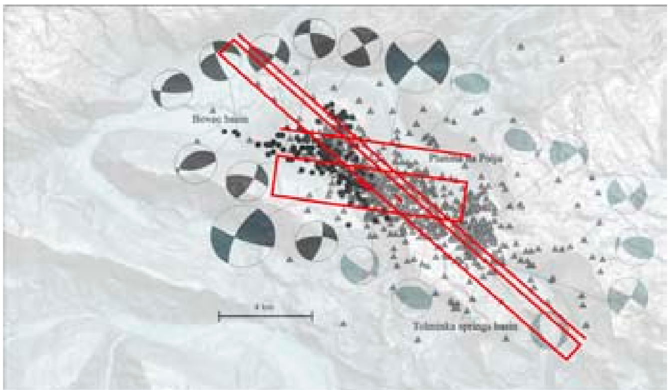

Fig. 2 – Spatial distribution of aftershock sequences of the 1998 and 2004 Ravne Fault earthquake events. Grey triangles depict the 1998 M_W= 5.6, black circles the 2004 M_W= 5.2 earthquake seismic sequences, respectively. The grey and light-greyish stars represent the 1998 and 2004 main shock locations, respectively. Grey-coloured focal mechanism belong to the 1998 (ZUPANČIČ *et alii*, 2001), the black solutions to the 2004 events (KASTELIC *et alii*, 2006). Red boxes represent the sources for both main shocks of the two seismic sequences, with the geometries obtained from their focal mechanisms and dimensions in agreement with geometrical empirical relationships (WELLS & COPPERSMITH, 1994).

(M_W=5.7) and 2004 (M_W=5.2) earthquake sequences were characterized by focal mecanisms ranging from dextral strike-slip to almost pure reverse faulting (KASTELIC *et alii*, 2006; Fig. 2). The main shocks of both earthquakes delineate prevailing dextral strike-slip movements on steep SW dipping planes. The 1998 earthquake cluster follows a NW–SE trend, with the main shock located approximately at 4.5 km from the fault's NW tip, whereas the SE end of the cluster reaches the Tolminka Springs basin. Focal mechanism solutions for stronger aftershock events indicate thrust or reverse movements on N dipping fault planes on both ends of the cluster, all within the first 7 km of the crust (ZUPANČIČ *et alii*, 2001). The earthquake did not cause surface faulting, but it did (re)activate a 12 km long and 7 km wide rectangular fault plane with an average slip of 18 cm (BAJC *et alii*, 2001). The 2004 earthquake was weaker and also did not cause surface faulting. The epicentre of the main shock was located about 1 km from the 1998 main shock location. This event and its aftershock sequence were also confined to shallow crustal levels. The spatial distribution of aftershocks is not as homogeneous in direction as for the 1998 cluster. Two distinctive branches of aftershocks can be observed for the 2004 sequence: one line continues in a NW–SE direction rupturing an area further NW of the 1998 cluster, while the other line branches off in an E–W direction (Fig. 2). The computed focal mechanisms for the stronger aftershocks (KASTELIC *et alii*, 2006) show similar kinematics as the main shock, the difference being a larger dip-slip component for some aftershocks, indicating oblique dextral-reverse movements on steep to moderate-steep NW–SE oriented fault planes and oblique reverse-dextral and reverse movements on E–W oriented, moderate-steep faults.

DISCUSSION

Knowing and understanding the geometry, time history and recent seismic destribution is essential in providing a reliable seismotectonic model and seismogenic potential assesment of a fault that has undergone multiple tectonic phases. In the case of Ravne Fault it was proven that the original geometry of the fault plane connected to SW verging thrusting phase plays an important role also in the recent seismic behaviour of the fault zone (KASTELIC *et alii*, 2008). During both the recent seismic sequences recorded in the Ravne Fault zone the main shocks occurred on SW-dipping subvertical fault planes, while the aftershocks were distribued on NE to N dipping fault planes related to the older thrusting phase. Of important significance is also the presence of the E-W thrusting phases within the fault zone, that caused disintegration and displacements of the NW-SE oriented thrust zone, and formation of local geometrical barriers that are governing the seismic distribution acting as segment boundaries. Examples of such behaviour can be found at both tips of the Ravne Fault. To the SE, the Tolminka Springs basin, an E-W trending thrust system meets the NW-SE oriented fault zone causing its displacement and formation of a transtensional basin that acted as a stopping barrier for the SE propagation of the 1998 earthquake sequence. From this location further to the SE the fault trace is getting more and more discontinous and slowly fading away, although some reports show its continuation in the SE direction for further 15 km (GRAD & FERJANČIČ, 1968). At the NW tip of the fault zone, the surface expression of the fault trace is lost in the Bovec basin under the Quaternary sediment infill, while in the NW slopes above the basin no fault trace can be observed. Close to the location of NW-SE oriented fault trace entering the Bovec basin is also the location of the intersection with the E-W oriented fault plane that was reactivated during the the 2004 earthquake sequence.

Given such structural setting three different seismotectonic scenarios can be envisaged:

a) if the existence of the SE continuation of the Ravne Fault zone with a length of about 15 km is established, the coseismic rupture of this new segment would result in an earthquake of magnitude similar to that of the 1998 event;

b) with the same assumption, the rupture of the entire Ravne Fault zone by breaching of the Tolminka Springs basin segment boundary, would produce a stronger earthquake. Taking into consideration the length of the fault trace and keeping the geometry and kinematics of the 1998 source, a Mw=6.1 earthquake is proposed by empirical relationships (WELLS & COPPERSMITH, 1994);

c) the coseismic rupture of the E-W oriented thrust plane already activated during the 2004 earthquake sequence, would result in a Mw=5.5 earthquake.

The model of segmentation applied in this case study can be applied also to the other fault systems of the region, which share the same geometry and the same structural development as the Ravne Fault. One of these fault systems is the NW-SE oriented Idrija Fault, responsible for the 1511 M=6.9 earthquake (FITZKO *et alii*, 2005) that is the strongest earthquake recorded in the region. Given the continuation of the fault trace to the SE, a higher magnitude earthquake with strike-slip motion is predicted by our model that is in accordance with the data of known seismicity. By taking into consideration all the data known we can improve the understanding of recent and future seisimic processes of a particular region and fault systems and therefore contribute to more realistic and reliable seismogenic potential assesments.

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